Upper-Ocean Influences on Hurricane Intensification Modeling

by

Christopher Gerard DesAutels

Submitted to the Department of Earth Atmospheric and Planetary Sciences
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Abstract

Hurricane intensification modeling has been a difficult problem for the atmospheric science community. Complex models have been built to simulate the process, but with only a certain amount of success. A model developed by Dr. Kerry Emanuel is much simpler compared to previous studies. The Emanuel model approaches hurricane intensification as an ocean-controlled process where the upper-ocean heat content limits intensification. It is shown that this ocean-based model can produce very accurate results when the true structure of the ocean can be determined. The Ocean Topography Experiment (TOPEX) provides an opportunity for the model to be tested through the use of satellite altimetry. Measurements of the mixed layer depth and upper-ocean heat content are incorporated into the model for Hurricanes Bret, Gert, Opal, Mitch and Dolly. This technique is shown to be quite reliable for many storms, especially in the Gulf of Mexico. Limitations are examined where this method breaks down and improvements are suggested for its development into a forecasting tool.

Thesis Supervisor: Dr. Kerry Emanuel
Title: Professor

Acknowledgments

Firstly, would like to thank Dr. Kerry Emanuel, for his guidance during the course of this thesis. His advise and direction allowed for this to be a productive and enjoyable experience, even during the the most harried times. I would like to thank Jennifer Cheng for her repeated reviews of this paper and unending support. I would also like to thanks my parents who have always unconditionally supported me in the crazy things I try to do. It has always meant a tremendous amount to me.

To my fellow students in the Geosystems program, I would like to extend my appreciation for an enjoyable year, and for all the support offered during long evenings of work. Finally I would like to thank MIT and the EAPS department for supporting me financially during this year of study.

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Chapter 1

Introduction

Every year about a dozen tropical storms form over warm ocean waters of the Atlantic. Several intensify into hurricanes and head towards the coast, threatening human lives and potentially causing substantial property damage. As a storm develops, there are two main characteristics that need to be predicted: intensification, and track. Models for the track of a hurricane have seen quite extensive development over the past years. Comparatively, hurricane intensification has been somewhat less studied. At present, most models are either based on extremely complex representations of the environment, or on statistical predictions. The Geophysical Fluid Dynamics Laboratory (GFDL) model is an example of the former (Kurihara et al. 1995), while the Statistical Hurricane Intensity Forecast (SHIFOR) model serves as a baseline statistical model (DeMaria 1997). Both of these methods are far from optimal. Full physics models such as GFDL are computationally expensive, with many running only slightly faster than real-time. Statistical models ignore important physical considerations and are limited in reliability.

Presently, there is a model under development by Dr. Kerry Emanuel at Massachusetts Institute of Technology which takes a somewhat different approach. This model is computationally simpler, relying on an axi-symmetric representation of the storm system (Schade et al. 1999). Special emphasis is placed on the interaction of the hurricane with the upper-ocean. The upper-ocean heat content serves as a limiting factor on hurricane intensification. This prominent role of the upper-ocean makes it necessary for us to develop a better understanding of how the upper-ocean varies, and how it can be measured. If the Emanuel model proves reliable, it may point to a new direction where the ocean plays a much more important role in hurricane intensification modeling.

In this paper I will first demonstrate how the upper-ocean and atmosphere interact to define the thermodynamic cycle of a hurricane. I will then present a possible method for quantifying the upper-ocean influences. I have found that reasonable predictions of the upper-ocean heat content can be determined using satellite altimetry available from the Ocean Topography Experiment (TOPEX). Some example storms from the historical record will be presented which demonstrate the promise of this approach. Finally consideration will be given to the limitations of this method, and directions that need to be taken in order to implement a reasonable hurricane intensity forecasting system.

Chapter 2

Hurricane Thermodynamics

2.1 Potential Intensity

The thermodynamic cycle that drives hurricane intensification is depicted in Figure 2-1. This model for intensification represents the hurricane system as an axi-symmetric Carnot cycle (Emanuel 1991). The system is assumed to be in a steady state where there is a balance between entropy input, output and dissipation. The process of hurricane genesis involves many complexities, so it is often most informative to examine the case of a fully developed storm and understand the energetics that sustain it.

The difference in temperature and saturation between the sea surface and the atmosphere boundary layer creates an enthalpy difference that fuels the Carnot cycle. The total work done by this Carnot cycle can be represented by

$$\frac{T_s - T_o}{T_s}\Delta s = \oint F \cdot dl \tag{2.1}$$

where T_o is the output temperature, T_s is the sea-surface temperature, Δs is the change in entropy from the edge to the center of the storm, and $F \cdot dl$ is the work done over an infinitesimal length dl. Starting from point 'A' in Figure 2-1, a parcel of air will travel towards the center of the storm, following the radial path shown. All along the path, enthalpy is transferred from the ocean to the atmosphere by a

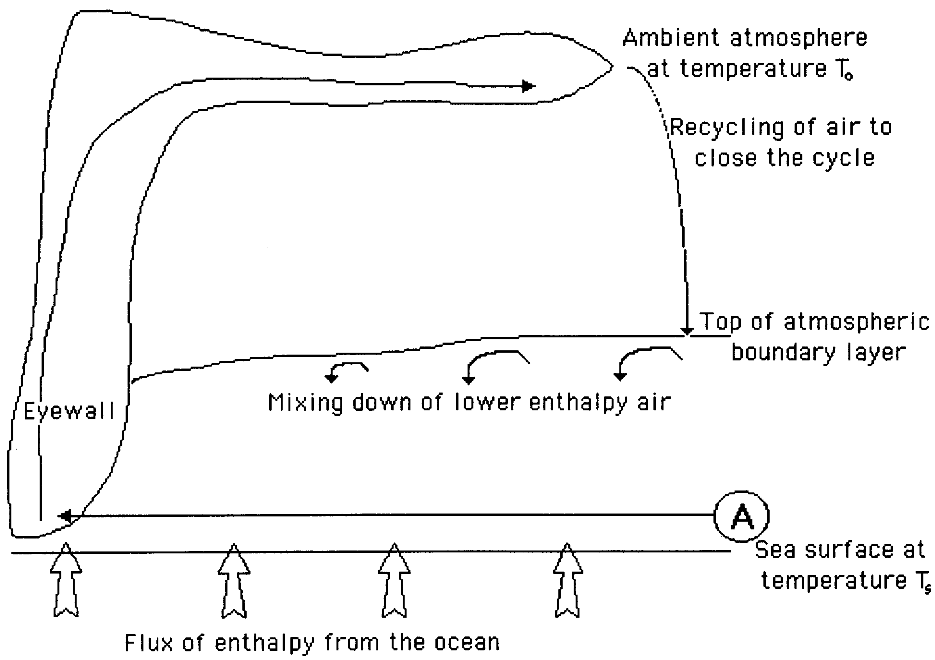

Figure 2-1: Thermodynamic cycle of a hurricane
Shows the input of entropy from the sea surface, and export to the ambiant environment.

exchange of both heat and moisture. This influx of enthalpy is balanced by convection within the boundary layer and entrainment of lower enthalpy air from the top of the atmospheric boundary layer. As the air parcel approaches the eyewall, the surface winds significantly increase. This causes a net influx of enthalpy into the atmosphere. To a first approximation, nearly all of the enthalpy exchange can be thought of as a happening directly under the eye-wall. The air parcel will then travel adiabatically up the eye-wall and out to the edges of the storm, where the heat will be dissipated. A certain portion of the heat will be recycled back to the beginning of the cycle, thereby closing the loop.

If we consider the balance of entropy in this cycle, there are three main contributions: the input of entropy from the sea surface,

$$\dot{s}_{in} = \frac{2\pi}{T_a}\int_{r_a}^{r_o} \left[C_K|V_a|(k_o^* - k_a)\right]\rho_a r dr \tag{2.2}$$

the export of entropy at the edges of the storm,

$$\dot{s}_{out} = \frac{2\pi}{T_o}\int_{r_a}^{r_o} \left[C_K|V_a|(k_o^* - k_a\right]\rho_a r dr \tag{2.3}$$

and dissipation occurring in the boundary layer.

$$\dot{s}_{diss} = \frac{2\pi}{T_a}\int_{r_a}^{r_o} \left[C_D|V_a|^3\right]\rho_a r dr \tag{2.4}$$

In a steady state 2.2, 2.3, and 2.4 will balance. Furthermore, if all of the enthalpy transfer can be approximated as occurring at the radius of maximum winds, then this balance will give us an equation for the maximum intensity of the storm

$$V^2 = \frac{C_k}{C_D}\frac{T_s - T_o}{T_o}(k_s - k_o)|_m \tag{2.5}$$

where C_k and C_D are the enthalpy and momentum exchange coefficients, and k_s and k_o are the specific enthalpies for saturated air at the ocean surface, and in the ambient environment evaluated at the radius of maximum winds. The ratio of C_k to C_D is assumed to be unity, but research shows that this may not be a trivial assumption (Emanuel, 1995). This estimate of maximum wind speed represents the maximum potential intensity of the storm based on a steady ocean-atmosphere environment.

2.2 The Role of Ocean Mixing

Based on these thermodynamic considerations a model can be built for the intensification of a hurricane. When this model is run the storm will quickly intensify up to its maximum potential intensity, and then remain at that level for an indefinite period of time. Figure 2-2 shows a sample run from such a model.

In reality, few large storms ever reach their maximum potential intensity (Emanuel

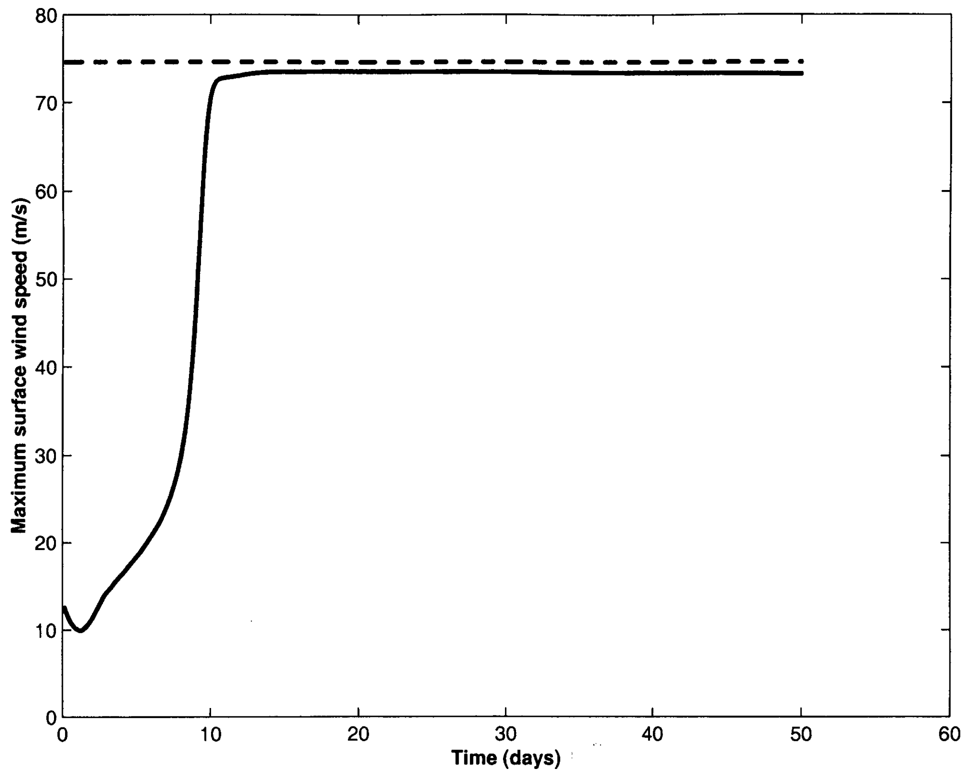

Figure 2-2: Hurricane model with no ocean interaction
The solid curve shows the intensification of the model under constant ocean-atmosphere conditions, and with no ocean feedback. The dashed line shows the level calculated from the approximate formula (2.5)

1988). Furthermore, once they have achieved their peak intensity they will often quickly decay. This is partially due to the translation of the storm through varying ocean-atmosphere environments. As a hurricane moves north over cooler water, the maximum intensity that the environment can sustain decreases. Even with this consideration the model will still overpredict a hurricane's intensity. There is one critical negative feedback that is supplied through the interaction of the hurricane with the upper-ocean that further limits the intensity of the storm.

As a hurricane translates across the ocean it can leave substantial cooling of the sea-surface temperature (SST) in its wake. A cooling of approximately 2-3 degrees can be seen quite clearly through the use of Advanced Very High Resolution Radar (AVHRR). The magnitude of this sea-surface cooling can be quite significant to the thermodynamic considerations outlined above. It has been determined that a temperature change of 2.5 degrees is sufficient to turn off the thermodynamic cycle completely. In this way, the cooling of the ocean surface by the passage of a hurricane constitutes a significant negative feedback. This negative feedback must be understood and quantified in order to accurately model hurricane intensification.

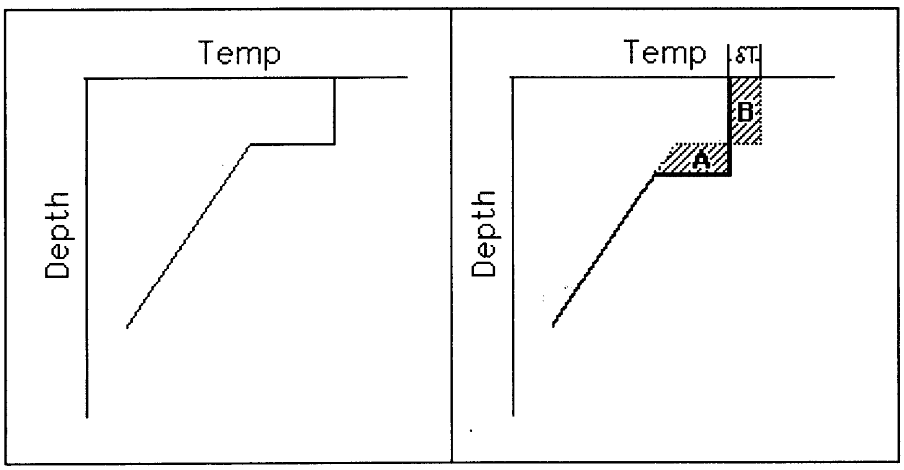

Figure 2-3: Temperature effects of a change in mixed layer depth
The left side shows the indisturbed upper-ocean temperature profile. The right side shows the results of turbulent vertical mixing. The heat that was original present in (A) has been mixed so as to cause the decrease (B). This corresponds to a decrease in SST of δT.

The cause of this cooling can be understood by examining the upper ocean temperature profile. The topmost layer of the ocean constitutes what is called the mixed layer. Water in this layer is constantly mixed such that the whole depth is maintained at a steady temperature. The depth of the mixed layer varies in both space and time with a depth of approximately 20 meters in the summer months, to over 100 meters during the winter. Below the level of this mixed layer the temperature decreases significantly with depth.

As a hurricane passes over the ocean, wind stress causes turbulent vertical mixing of a column of water. Due to the location of the maximum winds, this mixing can be approximated as happening directly under the eyewall of the storm. Figure 2-3 shows a schematic of how vertical mixing can cool the ocean surface. The left side shows the original temperature profile. As the mixed layer deepens a certain quantity of colder water is drawn up into the surface layer. This result in a proportional cooling of the entire mixed layer, and subsequently the sea surface. This process introduces the surface cooling which serves as a negative feedback to the intensification process. The degree of cooling is directly proportional to the amount that the mixed layer deepens. More intense winds result in deeper turbulent mixing and more cooling. For this reason weak to marginal strength storms, are not affected as much by this feedback. This negative feedback has its greatest effect on more intense storms. This property makes it of particular interest, since these are the storms that are of most concern to human populations.

Chapter 3

Method

3.1 The Model

The combination of maximum potential intensity, mixed layer depth, and the stratification of the colder waters below the mixed layer, constitute all of the environmental inputs to the Emanuel model (Emanuel 1999). Bathymetry is included for the purpose of determining when the mixed layer extends all the way to the ocean floor, and to define landfall. A storm is considered to have made landfall once the eyewall of the storm reaches land. At this point the ocean no longer supplies energy, and the storm dies off rapidly.

Climatological values for the input parameters have been calculated based on historical data. Monthly grids of mixed layer depth, and stratification are used with a grid resolution a 1^o x 1^o. Each monthly grid is assigned to the fifteenth of its respective month with values for other dates being determined by linear interpolation. Similarly constructed grids for climatological maximum potential intensity are used, but with a grid resolution of 2.5^o x 2.5^o. Bathymetry is also determined from a grid with 1^o x 1^o resolution.

In order to initiate the model, the operator must provide an initial intensity and rate of intensification for the storm. The saturation of the atmosphere is a measure of the initial intensification, and can be determined based on the first 1-2 days of storm growth. The track of the storm must also be specified, either from historical records, or based on a separate model. After the model has been started, it runs the full lifetime of the storm without additional input from the operator. Even when using climatological values, this model produces some impressive results for many prominent storms in the historical record (Emanuel 1999).

For those storms that are not accurately modeled, we need to consider the accuracy of the data that is being used. Climatological data does not contain any of the short-term eddies or variations that are present in both the atmosphere and the ocean. Because of the significant feedback connected to the ocean mixed layer it is important to quantify how the depth of this mixed layer varies with time.

3.2 Ocean Eddy Modeling

In order to accurately model the feedback of the upper-ocean, it is necessary to determine exactly how the upper-ocean varies, and identify the critical time and length scales. Ocean eddies are a significant contributor to hurricane intensification, because they signify local areas where the mixed layer is deeper and the heat content of the upper-ocean is greater. A group from the Naval Research Laboratory (NRL) has performed modeling of ocean eddies (Murphy et al 1999). The developed model takes the historical wind fields as input in order to numerically model the evolution of eddies. The study concentrates on the Gulf of Mexico and the Caribbean Sea. Results produced by this study are qualitatively comparable to actual eddy development and serve to demonstrate the variability of the ocean in this region. This variability could constitute a significant factor to hurricane intensification.

Figure 3-1 shows the approximate track that eddies follow as they travel through the Caribbean Sea and the Gulf of Mexico. The main circulation in this region consists of a current that enters the Caribbean between the Windward Islands, intrudes

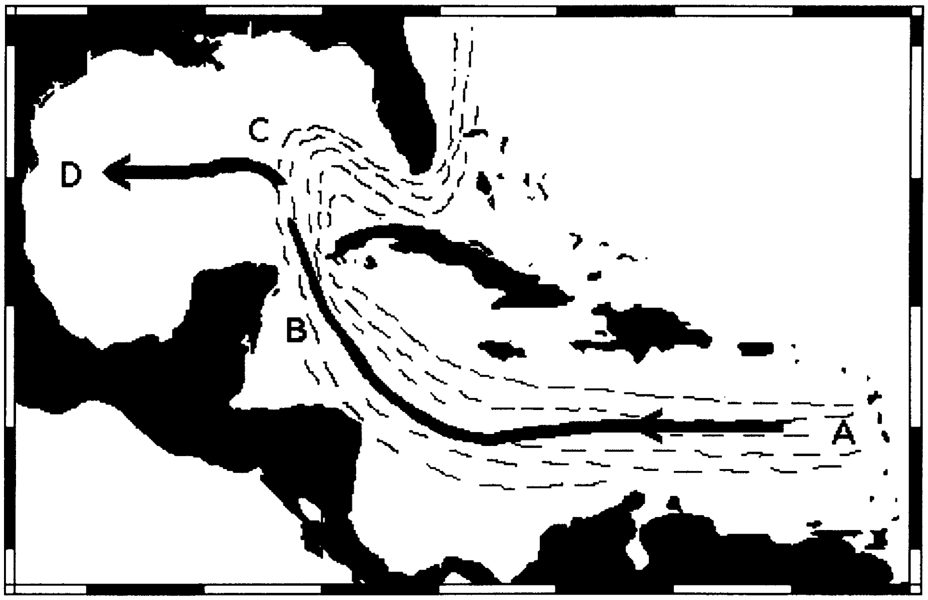

Figure 3-1: Eddy evolution in the Caribbean Sea and the Gulf of Mexico. A typical track is depicted showing (A) initiation by advection of potential vorticity through the Windward islands, (B) incorporation into the Loop Current, (C) the splitting off of eddies from the Loop Current, and (D) break-up on the western shores of the Gulf of Mexico.

into the Gulf in the form of the Loop Current, and then exits by way of the Straits of Florida where it joins the Gulf Stream.

Eddies in the Caribbean begin by the advection of potential vorticity between the Windward Islands. They are typically quite small as they begin to travel westward. During their passage though the Caribbean Sea, eddies can intensify and merge. Rapid eddy growth is not uncommon in the central Caribbean and significant growth can happen on a time scale of ten to fifteen days. These eddies will then enter the Strait of Yucatan where they are incorporated into the Loop Current. The Loop Current represents an area of locally deeper mixing and greater heat content. This current within the Gulf of Mexico varies slightly in its position with time. Occasionally eddies will separate from the Loop Current and travel westward across the Gulf of Mexico. These eddies are usually relatively constant in magnitude and transit the Gulf in about two months, after which time they break up off the coast of Southern Texas and Mexico. The total time scale for an eddy to make the trip from the Windward Islands to the western Gulf of Mexico is approximately ten months.

When a hurricane crosses one of these ocean eddies, it encounters a region of deeper mixed layer and increased heat content. This can lead to a significantly more intense storm than would be predicted based on climatological data. Climatological data contains no evidence of this short-term variability. It is desirable to develop some means to accurately measure the position and magnitude of these eddies so that their influences can be incorporated as a correction to the climatological data.

One method that allows for the tracking of ocean eddies is the use of satellite altimetry. Satellites such as the Ocean Topography Experiment (TOPEX) are equipped with a laser altimeter. This instrument allows for the measurement of the sea-surface height (SSH) to an accuracy of 2-3 centimeters. TOPEX orbits the earth with a between track spacing of approximately 2.8^o. Along the track of the satellite, data is collected at 7-km intervals. The total time for TOPEX to complete a mapping of the earth is 9.92 days. This data can provide an invaluable resource for tracking ocean eddies.

Sea height anomalies (SHA) can be caused by several different processes. The sea surface is significantly perturbed by the sea-floor topography. These effects can be estimated and removed from the data if the sea-floor topography is known. Additionally, the effects of tides must be removed based on a model of tidal motions. The remaining SHA are typically associated with any short-term variability in the upper-ocean. They allow for the tracking and measurement of ocean eddies. It is then necessary to develop a method for their incorporation into the hurricane intensification model.

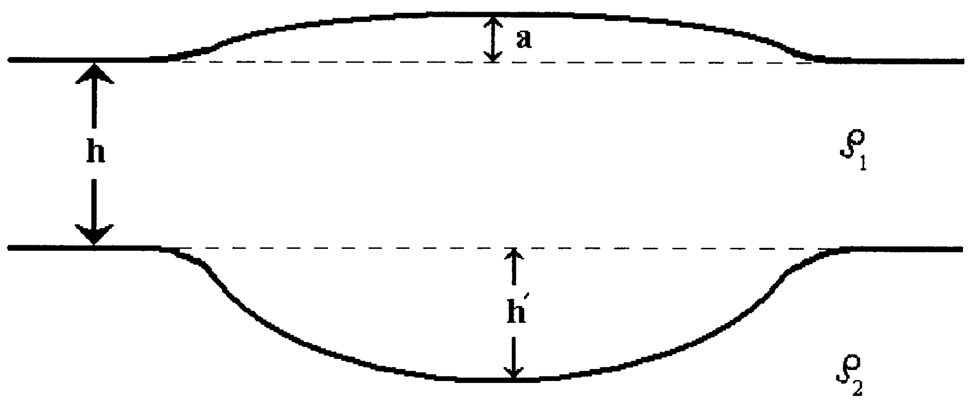

Figure 3-2: Two-layer model
Shows the values used to determine the mixed layer pertubation associated with a given SHA.

Translation of SHA to changes in the mixed layer depth can be done approximately by using a two-layer model of the ocean (Shay 1999). This model is depicted in Figure 3-2. In this model the ocean is approximated as consisting of two layers which differ in density based on temperature and salinity. The upper layer in this model is the mixed layer, while the lower is the colder stratified waters below. Based on buoyancy we can interpret changes in the sea surface height as an expression of the increase in the mixed layer depth. This increase can be calculated based on

$$H(x,y,t) = h(x,y,t) + \frac{\rho_2(x,y)}{\rho_2(x,y) - \rho_1(x,y)} \cdot a(x,y,t) \tag{3.1}$$

where h is the ambient climatological mixed layer depth, a is the sea height anomaly, H is the corrected mixed layer depth, and ρ_1 and ρ_2 are the densities of the upper and lower layers. The new mixed layer depth calculated in the presence of an eddy can be significantly deeper than climatological values. This will represent the potential for a significant and rapid increase in hurricane intensity.

Chapter 4

Results

For this study TOPEX data was acquired from the University of Texas, Austin Center for Space Research (CSR) (CSR 2000). Significant processing is needed to interpolate the along-track data onto a usable grid. TOPEX data is available from CSR with a 1^ox1^o resolution and was used here in that form. Analysis was concentrated on storms that formed and grew in the Gulf of Mexico and Caribbean Sea. Based on the NRL modeling study there is a good understanding of how eddies evolve in this region.

4.1 Hurricane Bret, 1999

Hurricane Bret was an early season storm which formed over the southern Gulf of Mexico and made landfall on the coast of Texas in late August 1999. It was speculated that the rapid intensification of Bret was due to its passage over a warm eddy that had traveled into the western Gulf of Mexico after breaking off of the Loop Current.

Figure 4-1a shows the model of the intensification of Hurricane Bret based solely on climatological values of the mixed layer depth. The dashed line shows the actual intensification based on observations, and the solid line shows the modeled intensification. There is a significant underestimation of the hurricane's intensity based on the climatological data. Additionally, the dotted line in Figure 4-1a shows the size of

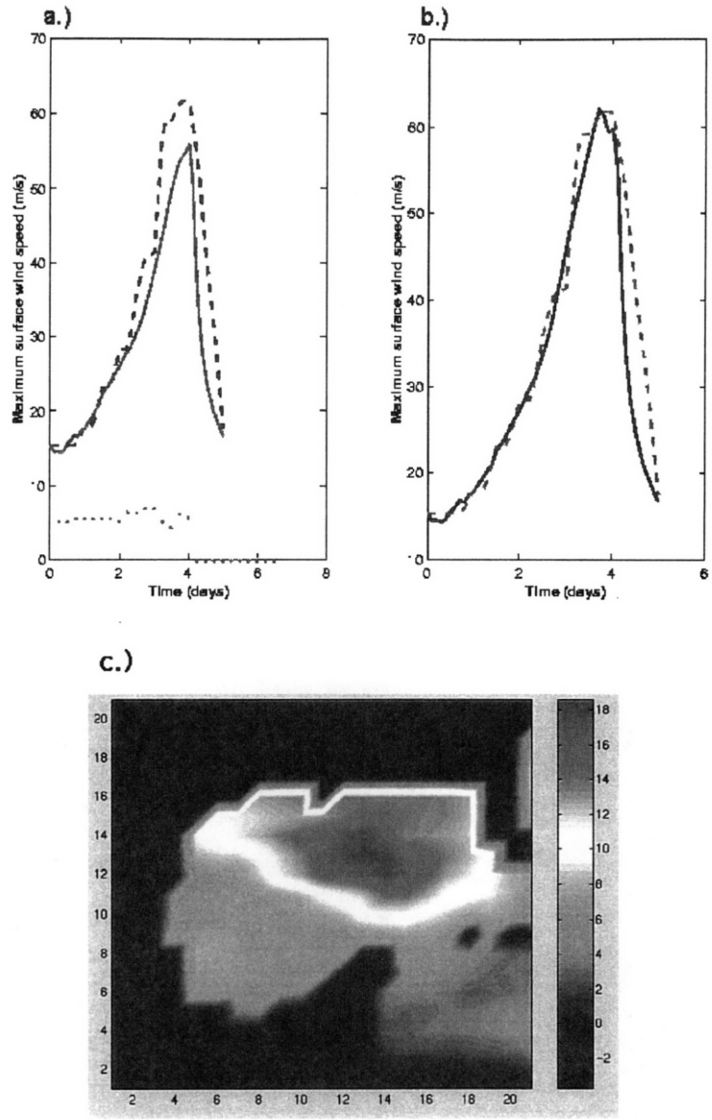

Figure 4-1: Hurricane Bret

a) Shows the intensification of the model for a climatological mixed layer. The solid line is the model storm, the dashed is the actual, and the dotted line is the magnitude of the anomaly in centimeters. b) Shows the intensification of the model with the inclusion of an eddy. Again, the solid line is the model and the dashed is actual. c) Shows the TOPEX derived SHA field used for this run.

the SSH anomaly over which Hurricane Bret passed. There is reasonable correlation between this anomaly and the underestimation of intensity present in the model.

A correction is added to the mixed layer depth based on the simple two-layer model. Values of the dimensionless term $(\frac{\rho_2}{\rho_2-\rho_1})$ are estimated from calculations by Shay (1999). For storms in the Gulf of Mexico 400 is found to be a typical value. Results of the model with a correction to the mixed layer depth are presented in Figure 4-1b. The model has now accurately predicted both the time and magnitude of maximum intensity to within expected errors of the historical data.

A plot of the TOPEX field used for this run is included in Figure 4-1c. This plot represents the TOPEX cycle that occurred just prior to the hurricane's growth in this region. It is necessary to use the prior cycle so as to avoid measuring the influence that the hurricane has on SHA. This practice assumes that eddies do not change on less than a ten day time scale. For the Gulf of Mexico this seems to be a reasonable assumption based on the NRL modeling studies.

The eddy can been seen as the light shaded region in the southwestern corner of the Gulf of Mexico. In this case, the additional heat present in the eddy seems to supply the proper correction for modeling this hurricane. It was the only parameter that was corrected for short-term variability. All other parameters were left at their climatological values. This indicates a particular sensitivity to the heat content of the upper ocean mixed layer.

4.2 Hurricane Gert, 1993

Hurricane Gert formed in the Caribbean Sea, but did not intensify until it crossed the Yucatan Peninsula and entered the Gulf of Mexico. In order to avoid some difficulties associated with the model's landfall algorithm, the model was initialized

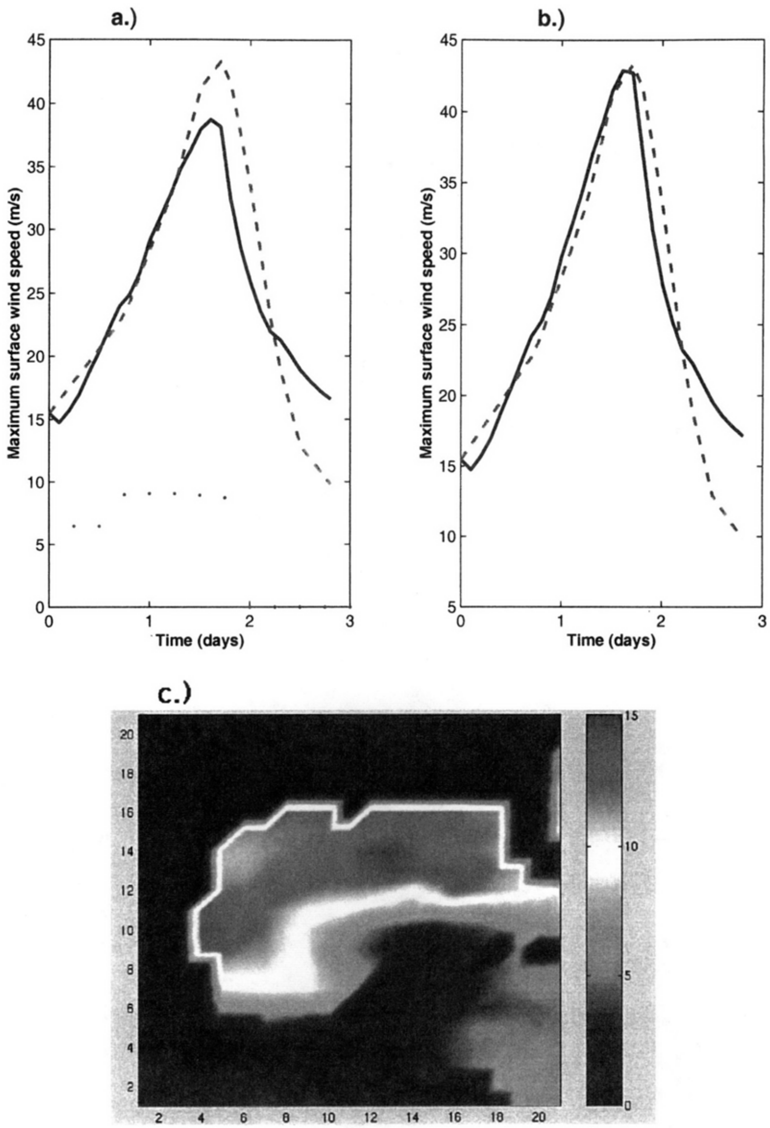

Figure 4-2: Hurricane Gert

a) Shows the intensification of the model for a climatological mixed layer. The solid line is the model storm, the dashed is the actual, and the dotted line is the magnitude of the anomaly in centimeters. b) Shows the intensification of the model with the inclusion of an eddy. Again, the solid line is the model and the dashed is actual. c) Shows the TOPEX derived SHA field used for this run.

after the storm had entered the Gulf of Mexico. A plot for the initial model run with climatological mixed layer depths is shown in Figure 4-2a. As with Hurricane Bret, there is a significant underestimation of the peak intensity. Figure 4-2b shows the intensification once a correction has been applied based on TOPEX data. This correction was applied in the exact same manner as with Hurricane Bret, using the same value of 400 in order to determine the mexed layer correction. A plot of the TOPEX field used is included in Figure 4-2c. Once again the results suggest that upper-ocean influences were the main factor that led to an underestimation of storm intensity.

4.3 Hurricane Opal, 1995

Hurricane Opal is one of the most cited examples of a hurricane encountering and being significantly influenced by an ocean eddy (Krishnamurti et al 1998, Shay 1999). Like Hurricane Gert, Hurricane Opal initially formed in the Caribbean Sea and traversed the Yucatan Peninsula before entering the Gulf of Mexico. For the same reasons, we initialize the model storm after it has entered the Gulf of Mexico. Figure 4-3a shows the actual intensification and model intensification based on climatological data.

Hurricane Opal intensified quite rapidly and unexpectedly after it entered the Gulf of Mexico. Speculation has been that the ocean eddy was a primary factor in this rapid intensification. The model based on climatological values seems to suggest something different. There is an observable underestimation of peak intensity, and a lag in the time of maximum intensity. However, these errors are not very large. The climatological model has already simulated the rapid deepening of this storm. Corrections to the mixed layer seem to be of a second order importance to this process. Figure 4-3b shows the result of the model once the ocean eddy influences are included. The inclusion of the eddy results in a slight improvement in modeling the time and level of peak intensity. The significant result for this storm was that the

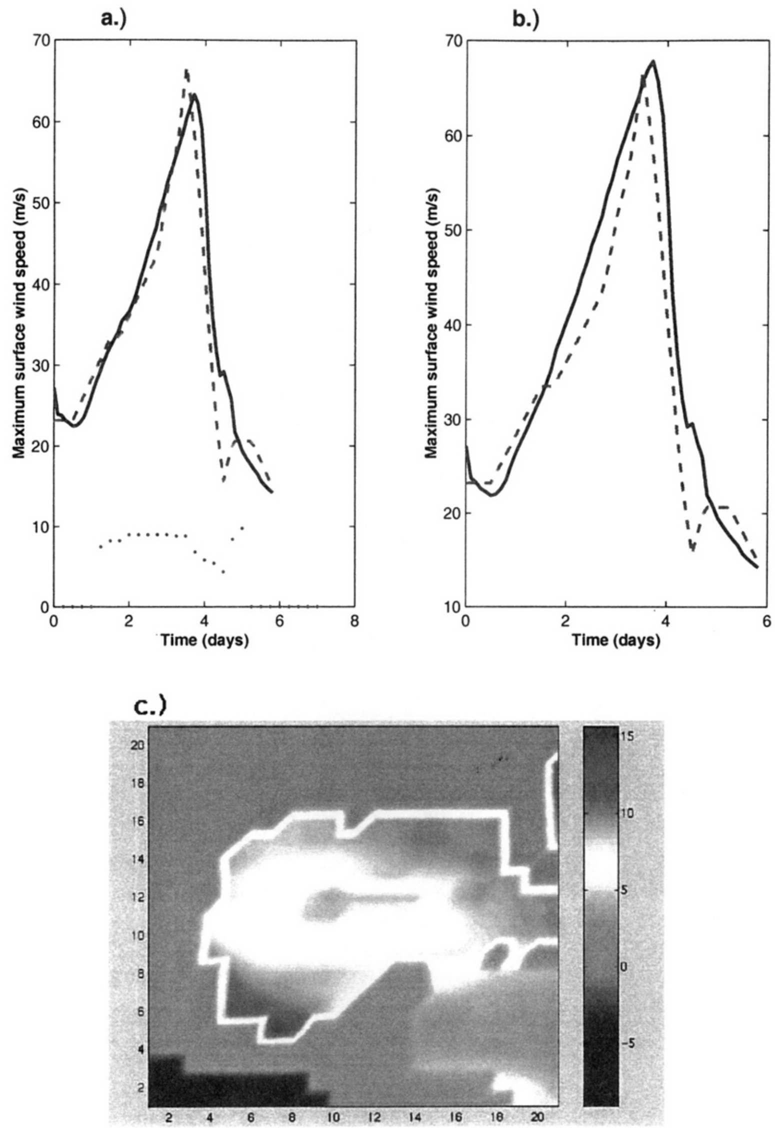

Figure 4-3: Hurricane Opal

a) Shows the intensification of the model for a climatological mixed layer. The solid line is the model storm, the dashed is the actual, and the dotted line is the magnitude of the anomaly in centimeters. b) Shows the intensification of the model with the inclusion of an eddy. Again, the solid line is the model and the dashed is actual. c) Shows the TOPEX derived SHA field used for this run.

Emanuel model was able to predict the rapid intensification that previously had been considered unexpected.

4.4 Hurricane Mitch, 1998

Unlike the prior three storms, Hurricane Mitch reached its peak intensity while in the Caribbean Sea. This fact is significant when considering the differing evolution of eddies in this region. According to the NRL study it is known that eddies in the Caribbean Sea can merge and intensify on relatively short time scales. This will prove significant when considering the evolution of Hurricane Mitch.

The intensification of Hurricane Mitch based on climatological values of the mixed layer depth is shown in Figure 4-4a. There is an obvious underestimation of the peak intensity. The value of the dimensionless scaling parameter ($\frac{\rho_2}{\rho_2-\rho_1}$) is slightly smaller in this region, and has a value of approximately 350 (NOAA 2000). Application of a correction based on TOPEX results in a slight improvement, as can be seen in Figure 4-4b. However, the model still significantly underestimates the peak intensity.

There are several factors that combine to cause the breakdown of this model. The first is the variability of eddies in the Caribbean Sea. As has already been stated, eddies in this region can merge and grow over times scales comparable to the ten day cycle of TOPEX data. Examination of the prior TOPEX cycle shows that the eddy which Hurricane Mitch passed over had grown substantially over the previous ten days. It is conceivable that the eddy continued to grow during the next two days, before Mitch passed over. This would lead to increased intensification. Our limited time resolution of ten days seems insufficient for this example.

In addition, Hurricane Mitch happened to pass directly over the peak of this particular eddy. In general, ocean eddies are of the same scale as the one degree grid

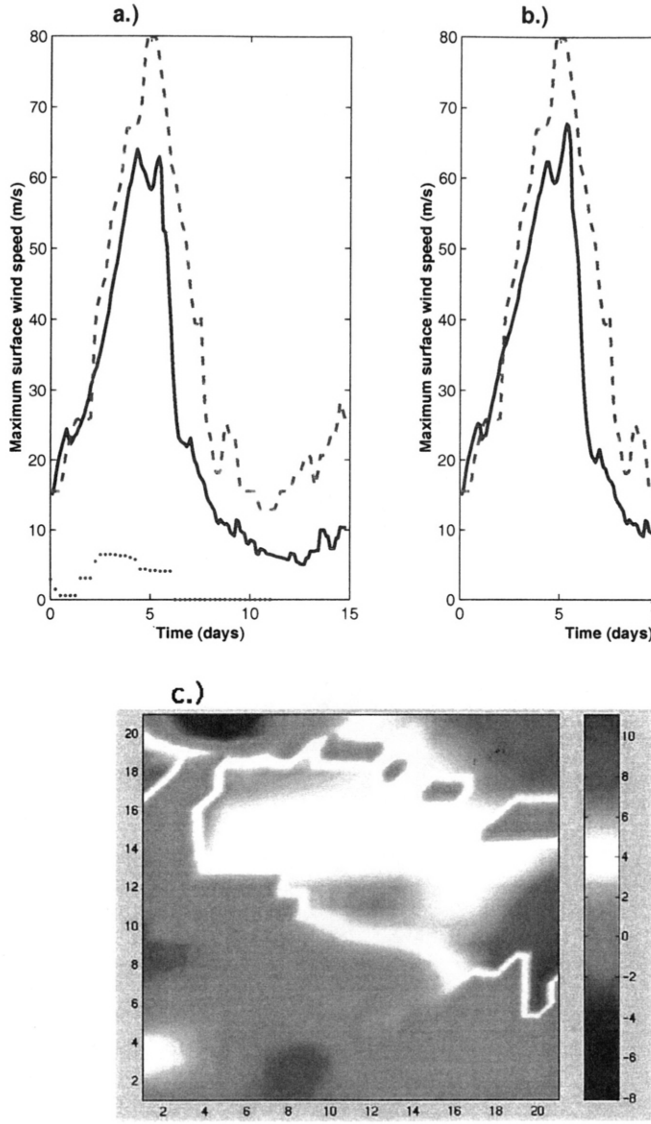

Figure 4-4: Hurricane Mitch
a) Shows the intensification of the model for a climatological mixed layer. The solid line is the model storm, the dashed is the actual, and the dotted line is the magnitude of the anomaly in centimeters. b) Shows the intensification of the model with the inclusion of an eddy. Again, the solid line is the model and the dashed is actual. c) Shows the TOPEX derived SHA field used for this run.

spacing used in this study. Mixed layer depths between grid points are calculated by linear interpolation. This process can lead to significant underestimation of values within one degree of the peak. It has been seen that for eddies of this scale, an underestimation of the peak values of 25% to 35% is not uncommon. For storms such as Mitch which pass within one degree of the peak of an eddy, this can be a significant effect.

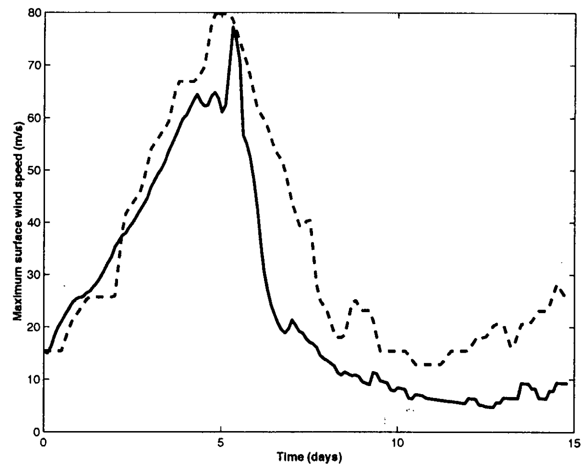

Figure 4-5: Hurricane Mitch approximation
Approximate correction included for grid resolution and continued intensification.

The model run shown in Figure 4-5 includes an approximation for these two errors. With this estimated increase, we have been able to improve our model of both the time and level of peak intensity for this storm. This result identifies some limitations caused by the resolution of our data that need to be considered. In certain cases, a one degree resolution may not be sufficient, nor may the ten day repeat cycle of TOPEX be frequent enough.

4.5 Hurricane Dolly

Hurricanes Bret, Opal, and Gert all intensified while in the same region of the Gulf of Mexico. All experienced significant underpredictions of peak intensity when run with climatological mixed layer depths. The corrections added through the use of SHA data allowed for fitting of these storms to within expected errors. In order to

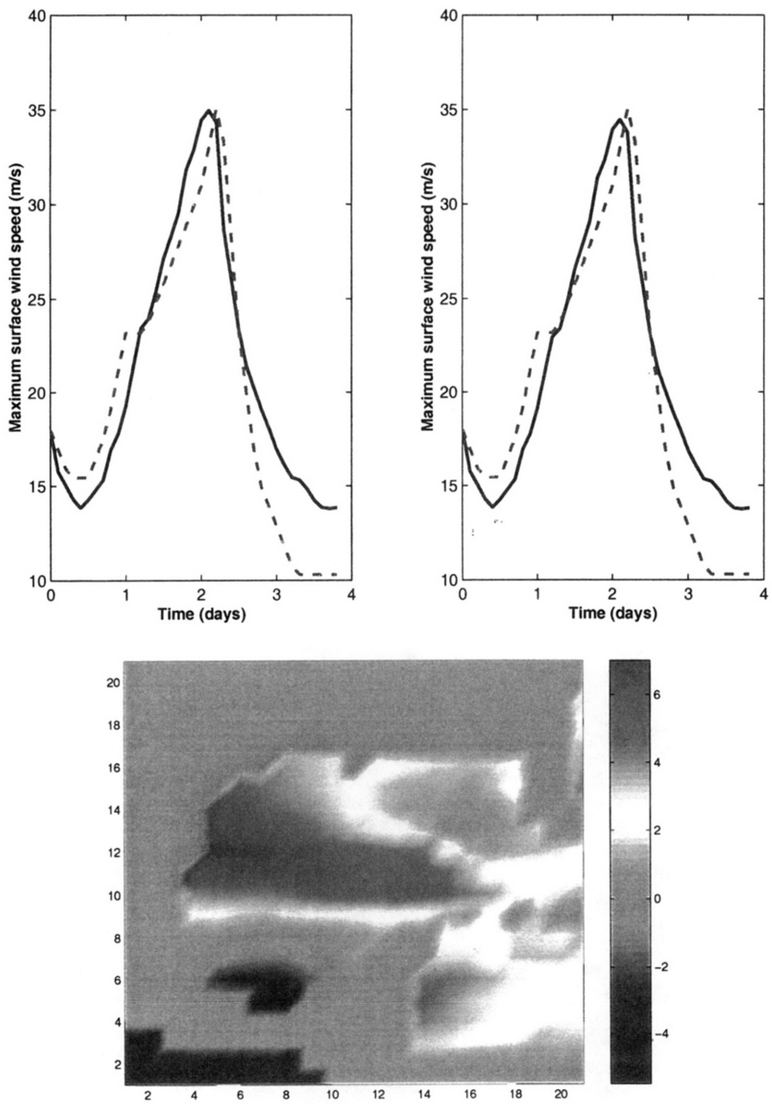

Figure 4-6: Hurricane Dolly
a) Shows the intensification of the model for a climatological mixed layer. The solid line is the model storm, and the dashed is the actual. b) Shows the intensification of the model with the inclusion of an eddy. Again, the solid line is the model and the dashed is actual. c) Shows the TOPEX derived SHA field used for this run.

confirm the validity of these results, Hurricane Dolly was considered as a control run.

Hurricane Dolly also intensified while in the western Gulf of Mexico. In contrast to the other storms studied, Hurricane Dolly did not display an underprediction of peak intensity. This can be seen in Figure 4-6a. Hurricane Dolly was large enough that the ocean mixed layer was serving as a limitation on intensity. This means that in the presence of a warm eddy, the model would react and possibly intensify. Failures could result for runs which had run well with climatological mixed layers. It needs to be determined whether TOPEX provides us with a repeatable process that can be applied to all storms in this region.

The results of adding the TOPEX-derived mixed layer correction are shown in Figure 4-6b. There is virtually no change in the intensity profile. This is an encouraging result. It shows that this method provides an accurate correction for storms that do encounter an ocean eddy, without negatively impacting storms that do not. This confirmation is necessary if TOPEX is to be used in a forecasting system.

Chapter 5

Conclusions

This study has demonstrated two important points. First it has been shown that that the Emanuel model can be an accurate model of hurricane intensification when upper-ocean influences are taken into account. This serves to further validate the ocean-based premise on which this model is formed. Since ocean evolution proceeds on a slower time scale than atmospheric evolution, there is significant hope for making advances in hurricane intensity predictions. Concentration now needs to be put on accurately measuring the ocean and recognizing this as a critical parameter.

Secondly, this study has sought to take the first step towards building a system that can perform as part of a dependable forecasting system. TOPEX data has shown to be a good measurement of variability in the upper-ocean. The ability to resolve eddies and estimate their influence is a significant development.

There are several steps that still need to be taken. Resolution needs to be improved, both spatially, and temporally. Finer spatial resolution calls for more robust interpolation algorithms. These can be performed either within or exterior to the intensification model. Approximating spatial changes of less than one degree as linear is not sufficient when considering ocean eddies.

Resolution in time has to be similarly increased. In the Gulf of Mexico, a ten day time resolution seems to be sufficient. There is little eddy growth in this region and translation is slow. In the Caribbean Sea however, growth is too rapid for this time scale. Increased measurements are needed to better resolve eddy growth. This should be possible through the use of additional space-based altimetry systems. Currently the European Remote Sensing (ERS) satellite provide a potential second station from which to gather altimetry data. The combination of satellites should allow for more frequent sampling, and more accurate measurements. Additionally a more complete understanding of eddy growth and evolution has to be developed for both the Caribbean Sea and the Atlantic Ocean as a whole. Inclusion of these eddies into the Emanuel model has shown great potential for accurate hurricane intensification modeling.

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